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THE BACKGROUND OF DETONATION.

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A determination of the relative merits of various fuels for use in high compression engines is the object of experiments being conducted at the Bureau of Standards for the National Advisory Committee for Aeronautics. Inasmuch as the tendency of a fuel to detonate often makes it unsuitable for such use, a consideration of the general subject of detonation has formed the initial step in this investigation. The purpose of this note is not to summarize the available information on the subject but to discuss a phase which seems to have received relatively little attention.

In most discussions of detonation attention has been focused on the rate or the nature of the combustion. Charge temperatures and pressures before combustion have been considered from the standpoint of their influence on this rate rather than from the standpoint of their influence upon the temperatures and pressures after combustion. This does not imply that investigators have failed to appreciate this latter influence but that they have thought of it as a sort of necessary background fixed by the compression ratio and so have turned their attention to a factor that could be altered, namely, the rate

of combustion. It is believed, however, that a careful scrutiny of this "background" will throw considerable light on some of the results that have been obtained in detonation research and to this end the following discussion is devoted.

Fig. 1, which presents results obtained from a one-cylinder engine, forms a convenient starting point. In this figure and throughout the paper, the presence or absence of detonation should be understood to mean the presence or absence of the metallic ringing sound characteristic of detonation.*

As indicated in the figure, detonation was only apparent at spark advances between 25° and 55° before center. More interesting is the fact that with this engine detonation only occurred when the explosion pressure as measured was somewhat greater than 450 pounds per square inch. From this, one would conclude that for a given engine the explosion pressure must exceed a definite value if detonation is to result. Such a conclusion is a natural consequence of the common belief that the sound which serves to identify detonation arises from a deflection or vibration of the combustion chamber walls. It seems logical therefore to consider such changes of engine condition as are known to affect detonation and to estimate the effect of such changes upon the explosion pressures.

Compression ratio deserves first attention as it is known to

* For a discussion of quantitative methods of measuring detonation, see "Methods of Measuring Detonation in Engines," by Thomas Midgeley, Jr., and T. A. Boyd. Journal of the Society of Automotive Engineers, January, 1922.

exert great influence upon the tendency of an engine to detonate. Accordingly, calculated explosion pressures for several compression ratios have been plotted in Fig. 2. These have been computed as though the entire charge were burned at top center with no heat loss. Obviously explosion pressures thus calculated should exceed those obtained in practice. Nevertheless they form a satisfactory basis for comparison provided actual rates of burning and heat dissipation are approximately the same for all the conditions compared. Moreover, ground for believing that this assumption is not far from the truth comes from the testimony of numerous investigators that they have obtained maximum power with nearly the same spark advance over a wide range of fuels* and compression ratios.

In calculating the values for Fig. 2, the following familiar relations have been employed.

$$P_2 = P_1 \; r^n$$

$$T_2 = T_1 \; r^{n-1}$$

$$M = T_3 - T_2$$

$$P_3 = P_2 \left(\frac{T_2 + M}{T_2}\right) = P_2 \left(1 + \frac{M}{T_2}\right)$$

where

r = ratio of compression and expansion.

P_1 = absolute pressure at beginning of compression stroke.

T_1 = absolute temperature at beginning of compression stroke.

P_2 = absolute pressure at end of compression stroke.

T_2 = absolute temperature at end of compression stroke.

M = increase in mixture temperature due to combustion.

* All fuels give nearly the same maximum power at the same compression ratio.

T_3 = absolute temperature after combustion.

P_3 = absolute pressure after combustion.

n = exponent having experimental values ranging from 1.25 to 1.35.

In preparing Fig. 2, P_1 has been taken as 14.7 pounds per square inch, M as 2700°C and n as 1.3. In figuring T_1, the fresh charge has been assumed equal to the piston displacement in volume when at atmospheric pressure and at an absolute temperature of 320°C. In like manner the residual products of combustion have been assumed of a volume equal to the engine's clearance space when at atmospheric pressure and at an absolute temperature of 1273°C. Some values thus calculated are tabulated below*

r	T_1	T_2	P_2	P_3	T_3
4	393°C	595°C	89	494	3295°C
5	376	610	119	645	3310
6	365	625	151	806	3325
7	358	643	185	960	3343
8	353	660	219	1115	3360

* It should be remembered that the aim is a comparison rather than accurate determination of temperature and pressures. This justifies the omission of steps that otherwise would be essential. For example, the temperature increase produced by combustion has been taken as 2700°C for all compression ratios, although because of the smaller clearance volume of spent gas the amount of temperature rise should increase with the ratio (since less of the energy of combustion is expended in raising the temperature of the inert gas). An opposing tendency is the increase in specific heat that results from the higher compression temperatures of the higher compression ratios. The use of the same value of exhaust gas temperature for all ratios is open to similar criticism. An increase in expansion ratio tends to lower this temperature, which effect is opposed by a decrease in heat loss due to the decrease in combustion chamber surface. These various tendencies have been considered but are not included in the calculations as their combined influence should affect the comparative values less than 5%.

Attention has been directed repeatedly to the many tendencies toward an increase in combustion rate with an increase in compression ratio. A smaller volume through which the flame must spread and a smaller proportion of inert gas are two of the factors emphasized. All such tendencies would increase the differences shown in Fig. 2. The significant thing is that, neglecting all such possibilities, assuming no change in combustion rate, there would still be an increase in explosion pressure of over 125% produced by changing from a ratio of 4 to one of 8. This change of ratio would only increase the absolute temperature at the end of compression by 11% and the absolute temperature at the end of combustion by 2%. One is not surprised, therefore, that a well known British investigator concludes charge temperature to be of minor importance from a detonation standpoint.*

At this point it is well to consider Fig. 3, which presents some of the most interesting information that this investigator, Mr. Ricardo, has obtained from his variable compression engine. The figure shows data obtained by throttling the engine, at compression ratios above 4.8, to the point of detonation. The dotted line shows the I.M.E.P. obtained at full throttle with a non-detonating fuel. After operating at each ratio the compression pressure was measured with a gauge while the engine was driven by a motor at the same speed and throttle opening as before. The

* Harry R. Ricardo, "Transactions of the January, 1922 Meeting of the Society of Automotive Engineers." The conclusion quoted is expressed thus, "Our experiments appeared to show pretty clearly that detonation has very little connection with the temperature of compression, but is closely dependent upon the compression pressure."

The most striking lesson from this curve is that detonation occurs at very nearly the same compression pressure regardless of the compression ratio.

Inasmuch as this discussion is concerned with the relation of explosion pressures to detonation, an estimate of the probable explosion pressures for the conditions shown in this figure is in order. One might anticipate that the expansion of the gases after passing the throttle would cause an appreciable temperature drop. Calculation and experiment both show this effect to be negligible under the circumstances under consideration.* Another factor which is likely to influence the temperature at the beginning of compression is the proportion of exhaust gas present. This can be estimated rather closely by assuming that the weight of fresh charge at part throttle bears the same relation to the weight of charge at full throttle as the I.M.E.P. at part throttle bears to the I.M.E.P. obtained at full throttle with a non-detonating fuel. Actual experimental determinations of I.M.E.P. are given in the figure. Except for the use of the I.M.E.P. to estimate part throttle exhaust gas content, the method of calculation is the same as that used in obtaining Fig. 2. Although throttling an

* On p.109, of Bulletin No. 19, of the Engineering Experiment Station of Ohio State University, Prof. Norman discusses the laws governing this drop in temperature and calculates the following values:

Gas velocity in feet per second	50 -	100 -	200 -	300
Temperature drop in degrees C	0.1	0.4	1.8	4.2

Tests at the Bureau of Standards showed no decrease in manifold temperature when the throttle of an aviation engine was closed while it was being motored with the fuel supply cut off.

engine of fixed compression ratio tends to increase the proportion of exhaust gas to fresh charge, the calculations indicate that with the variable compression engine under the circumstances under discussion there is an accompanying decrease in clearance volume which neutralizes this effect. Thus over the range covered by the curves the exhaust gas expressed as a percentage of new charge varies less than 1. It follows that the temperature at the beginning of compression will remain nearly constant and values calculated on this basis are tabulated below.

r	T_1	T_2	T_3
4.8	388°C	620°C	3320°C
5.0	388	629	3329
5.5	388	648	3348
6.0	388	664	3364
6.5	388	680	3380
7.0	388	696	3396
7.5	388	710	3410

It will be recalled that the relation between explosion pressure and compression pressure is as follows: $\frac{P_3}{P_2} = 1 + \frac{M}{T_2}$. An increase in compression ratio means an increase in T_2 and hence a decrease in the value of this ratio. For this reason a higher explosion pressure will be obtained from a low compression ratio engine at full throttle than from a high compression ratio engine throttled to the full load compression pressure of the low ratio. This fact may be stated from a slightly different angle in this fashion, - to maintain a constant explosion pressure the compression pressure should increase slightly with increase in compression ratio.

Explosion pressures as calculated for Fig. 3 are tabulated below.

r	P_2 (Absolute Pressure)	P_3
4.8	113	606
5.0	113.2	599
5.5	114.2	589
6.0	116.2	589
6.5	119.2	592
7.0	123.2	601
7.5	127.7	612

The maximum variation in explosion pressures is seen to be less than 4% and the deviation from the average pressure about 2%. When experiment has shown detonation to be constant under the conditions of Fig. 3, and calculations show explosion pressures to have been constant, there is reason for a deepening conviction in the close relationship of explosion pressures to detonation.*

Scavenging, that is to say, removing all or part of the spent gases from the clearance space, increases detonation. This fact has been taken as convincing proof of the great influence exerted by small proportions of exhaust gas on the rate of flame spread. Very probably this influence exists and operates as supposed.

* On page 6 of "Recent Internal Combustion Engine Research," presented at the January, 1922, meeting of the Society of Automotive Engineers, Mr. Ricardo says: ".... the tendency to detonate depends in effect upon the compression pressure not, as I supposed, because the pressure has any marked influence, but rather because in any actual engine the compression pressure is in itself a measure of the proportion of inert diluent present in the cylinder."

The reader will perceive that the author's interpretation of the data is somewhat at variance with Mr. Ricardo's. It is regrettable that the scope of the paper does not permit citing the many views of Mr. Ricardo with which he is in hearty accord. The use of Fig. 3 is but one indication of his belief in the accuracy and value of Mr. Ricardo's experimental determinations.

It is true, nevertheless, that the effect of scavenging on detonation can be explained partially at least by its influence on the explosion pressure. This influence is twofold. First of all, removing the hot exhaust gases from the clearance space of the engine means a lower temperature at the beginning and hence at the end of compression. Reverting again to the relation $\frac{P_3}{P_2} = 1 + \frac{M}{T_2}$, it is clear that lowering T_2, increases the ratio and thus the explosion pressure. This holds true if M, the increase in temperature resulting from combustion, does not decrease. But M should increase since the energy of the fuel is expended in heating a smaller mass of inert gas. This then is the second tendency toward increased explosion pressure and consequently detonation. Calculated explosion pressures show a probable increase of over 25% for a scavenged in comparison with an unscavenged engine having a compression ratio of 4.

Another influence which vitally affects detonation is the ignition timing, the spark advance. As before, it is convenient to picture the charge burned at constant volume at a point in the stroke governed by the spark advance. This does not mean picturing the combustion as occurring at the same time as the spark but as always occurring at the same interval of time after the spark. The burning that takes place during this interval may be treated as the burning of a fuse that later fires the explosive. As shown when discussing the effect of compression ratio, the maximum explosion pressure should occur when the pressure prior to combus-

tion is greatest. Since the charge is compressed most at top center the maximum explosion pressure should result from a spark so timed as to cause the actual combustion to take place at that part of the stroke and retarding the spark so that combustion comes later should decrease the explosion pressure. For the engine from which the pressure measurements of Fig. 1 were taken the estimated ratio of the explosion pressures obtained with combustion at various angles past top center to what would have resulted from combustion at top center are given below.

Degrees of crank angle after top center at which equivalent instantaneous combustion occurs.	Explosion pressure in % of the pressure when equivalent instantaneous combustion occurs at top center.
0	100
10	94
20	84
30	72
40	59
50	49

This demonstrates that very considerable differences in explosion pressure would be expected from a change in spark advance even if the rate of combustion remained the same. When there is superimposed the influence of a change in rate, it is not surprising to find differences of the magnitude shown in Fig. 1. The pressure at the time of explosion should be the same whether combustion takes place at a given angle before top center or after. With combustion before center, however, barring the heat loss, the subsequent compression of the burned gases will increase the pressure

to a value in excess of that resulting from burning the charge at center. In practice it often happens that with an early spark the rate of heat loss exceeds the rate at which heat is produced by the compression of the burned charge so that the maximum pressure of the cycle is lower than with a less early spark. This accounts for the decreased pressures at the extreme spark advances of Fig. 1. Furthermore, it is not surprising that carbon-bisulphide, which preignites early in the stroke, does not detonate since the effect of preignition is that of a too early spark.*

The relative influence of spark advance and throttle opening on detonation is of considerable importance in connection with the use of high compression over-dimensioned engines. Such engines have too high a compression ratio to operate safely at sea level at full throttle with the spark advance that would give maximum power with a non-detonating fuel. Experiments at the Bureau have shown that for an emergency "take-off" such engines will develop more power if the spark is retarded to eliminate detonation than if the throttle is closed to produce the same effect.

Aside from its practical bearing on engine design, it is worth while to see whether the comparative influence of spark advance and throttle opening would be predicted from their influ-

* In the Journal of the Society of Automotive Engineers, September, 1930, C. F. Kettering says: "Using carbon-bisulphide as a fuel, we get a genuine preignition. This fuel ignites very early and the pressure rises rapidly but it will not knock. Preignition will not necessarily cause a knock, because it may be that the pressures will not rise higher than normal."

ence on explosion pressures. The theoretical indicator cards of Fig. 4 will aid the comparison. In this figure the dotted line indicates the pressures at full throttle with a non-detonating fuel and a compression ratio of 6.5. The problem is to obtain from this engine the maximum power that is possible with a fuel which because of detonation cannot be used with an unthrottled engine having a compression ratio in excess of 5.5 (the volumetric efficiency is assumed the same for both ratios). If explosion pressure controls detonation, the problem resolves itself into so adjusting spark advance or throttle as to restrict the explosion pressure to the value obtained with an unthrottled engine of 5.5 ratio. Since the explosion pressure with a 5.5 ratio is about 82% of that with a 6.5 ratio, an engine having the latter ratio must be throttled to about 82% of full load. (Taking into consideration the modifying factors discussed in connection with Fig. 3, gives 85% as a closer value.) The full curve of the figure shows the probable pressures under this throttled condition.

The other alternative is to retard the spark so that combustion does not take place until the piston has traveled far enough on the down stroke for the pressure to have fallen to the maximum compression pressure with the 5.5 ratio. A full heavy line shows the pressures under this condition. Since the engine receives a full weight of charge, the power should be less than that obtained with the non-detonating fuel only because the ratio of expansion after combustion is 5.5 in contrast with 6.5 with the non-detonat-

ing fuel and the optimum spark advance. The air cycle efficiency* for a 5.5 ratio is 94% of that for a 6.5 ratio. Thus retarding the spark to avoid detonation requires a 6% decrease in power against the 15% sacrifice which throttling entails.

From all the evidence presented it appears that a close relationship exists between explosion pressures and detonation and that, having calculated the explosion pressures for an engine condition at which detonation occurs, for any other engine condition the probable presence or absence of detonation can be predicted from a calculation of the probable explosion pressure. It does not follow necessarily that the uniform explosion pressures as here calculated produce the sound of detonation. There is evidence that there are local pressures which exceed these average pressures and to which should be charged both the sound and destructive effects of detonation. The evidence does indicate that if local high pressures exist they are proportional to the average pressures as calculated, inasmuch as the latter have proved an accurate index of the presence or absence of detonation.

Emphasis, thus far, has been placed on conditions that influence detonations even with the rate of combustion unchanged. Better appreciated and no less important is the influence of a change in combustion rate with other conditions remaining constant. In fact, detonation research has confined itself largely to attempts to influence this rate. The goal is a slowing down of the final stages of combustion. It may be neither necessary nor desirable

* Air cycle efficiency = $1 - \left(\frac{1}{r}\right)^{n-1}$ where $n = 1.4$ and r = expansion ratio.

to decrease the average combustion rate. Tradition tells us that it was the "last straw" that brought disaster to the back of a camel and similarly, it is the last rise in pressure that brings ruin to the head of a piston. An illustration will show how this disastrous peak pressure may be avoided by a slight change in the combustion rate. For the first condition assume that the piston is at top center, that all the charge has been burned and that the charge temperature is 3350°C. Assume also that a temperature drop of 250°C results from the heat dissipation during the next 10° of crank motion. For the second condition let it be assumed that when the piston reaches top center sufficient charge has been burned to have produced a temperature of (3350 - 250)°C and that the remainder is burned during the next ten degrees of crank motion at such a rate that the heat input shall just offset the heat dissipation and the pressure and temperature at 10° past top center be approximately the same as in the first case. The ratio of the pressure in the latter case to that in the former is $\frac{3350 - 250}{3350}$ or 93%. The only difference in power that should result is that due to a loss in efficiency chargeable to the decreased expansion ratio of the portion of the charge burned in the ten degrees after center. Calculation shows the net loss to be less than two-tenths of one percent. In short, a decrease of 7% in maximum pressure is obtained at the expense of a decrease of two-tenths of one percent in power.

Fig. 5 indicates in a general way why differences in spark plug position and combustion chamber shape change the rate at

which the charge is consumed. By means of the alternate light and dark areas the amount of surface swept by the flame from each spark plug in equal time intervals can be determined. The lower plots show total areas swept by flame in unit time plotted against time. In these figures the area under the curve at the left of any ordinate represents the total area swept by the flame up to that time. The upper flame spread diagrams are drawn as though the flame moved radially at a uniform linear rate. This assumption is admittedly false for the flame, at least in its initial stages, spreads at an accelerated rate. Moreover, in the engine it is not areas with which one is concerned but volumes and the problem is further complicated by the movement of one wall of the combustion chamber, namely, the piston head. Obviously, then there is no point in analyzing the figures to show which spark plug arrangement gives minimum detonation. Their sole aim is to show why a change in spark plug arrangement should make a difference in detonation.*

A discussion of the influence of changes in fuel characteristics upon detonation lies outside the province of this paper. Possibly the most hope of relief from detonation troubles lies in the ability to alter these characteristics, and much excellent work has been done in this field.**

* For a discussion of actual combustion chamber shapes and their influence upon detonation, see "Turbulence," by H. L. Horning, on page 579 of the Journal of the Society of Automotive Engineers, June, 1921.

** "Combustion of Fuels in Internal Combustion Engines," by C. F. Kettering, Journal of the Society of Automotive Engineers, September, 1920; "Combustion of Fuels in Internal Combustion Engines," by Thomas Midgely, Jr., Journal of the Society of Automotive Engineers, December, 1920.

Except in the case of the automobile engine the noise of detonation in itself is of no consequence. Detonation's seriousness lies in its high pressures and in the excessive heat loss which prevents the attainment of the power that would otherwise be possible. Most investigators have been made acquainted with this excessive heat dissipation by an increased loss to the jacket water whenever detonation has been present. In a preceding paragraph a comparison was made between the effect of burning all the charge at top center with a resultant temperature of 3350°C and slightly retarding the rate of burning so that the maximum temperature did not exceed 3100°C. Radiation varies approximately as the fourth power of the absolute temperature and would at top center be 35% greater with the higher temperature. It seems clear that much of the power loss that accompanies detonation can be attributed to excessive heat dissipation arising from a condition approximating the one just mentioned.

Preignition and detonation are now generally conceded to be entirely independent phenomena. Preignition is unusual, caused by a hot spark plug electrode, by an exhaust valve or by a piston head and depends upon the ignition temperature of the fuel. Changes in the design of these members will do much to prevent this trouble. The important fact is that such changes will be necessary with an increase in compression ratio unless the fuel has been prepared to eliminate preignition as well as detonation.

It may be mentioned in passing that overheating troubles are a more likely result of preignition than of detonation. This can

be illustrated best by assuming an extreme case of preignition with the charge ignited as it enters the cylinder and all burned by the beginning of the compression stroke. It is conceivable that the rate of heat dissipation during this stroke should be such that at top center the same pressure and temperature would result as when, under normal operation, the bulk of the charge is burned at top center. Pressures and temperatures during expansion would be the same for both cases. For the compression stroke however, the average temperature with preignition would have been in the neighborhood of 3000°C in contrast with 500°C under normal operation.

As stated in the outset, this paper's aim has not been to present a complete picture of detonation but to consider several more or less independent features of the problem which have received comparatively little attention. Whether these features belong in the background or foreground is immaterial so long as they are recognized as an essential part of the picture.

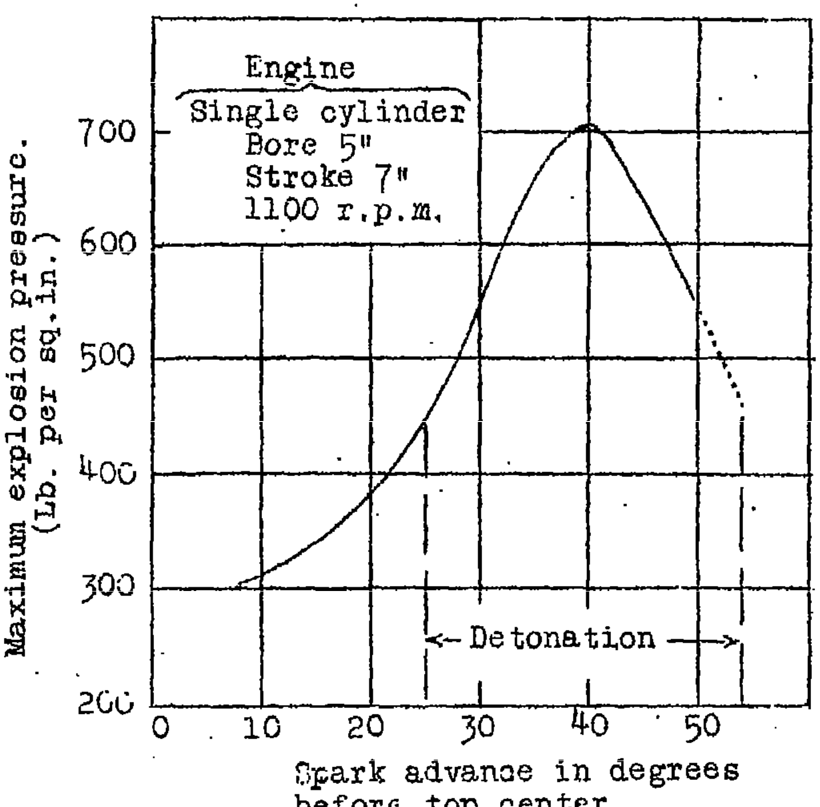

Engine
Single cylinder
Bore 5"
Stroke 7"
1100 r.p.m.
Maximum explosion pressure.
(Lb. per sq.in.)
700
600
500
400
300
200
Detonation
0
10
20
30
40
50
Spark advance in degrees
before top center.

Fig. 1.

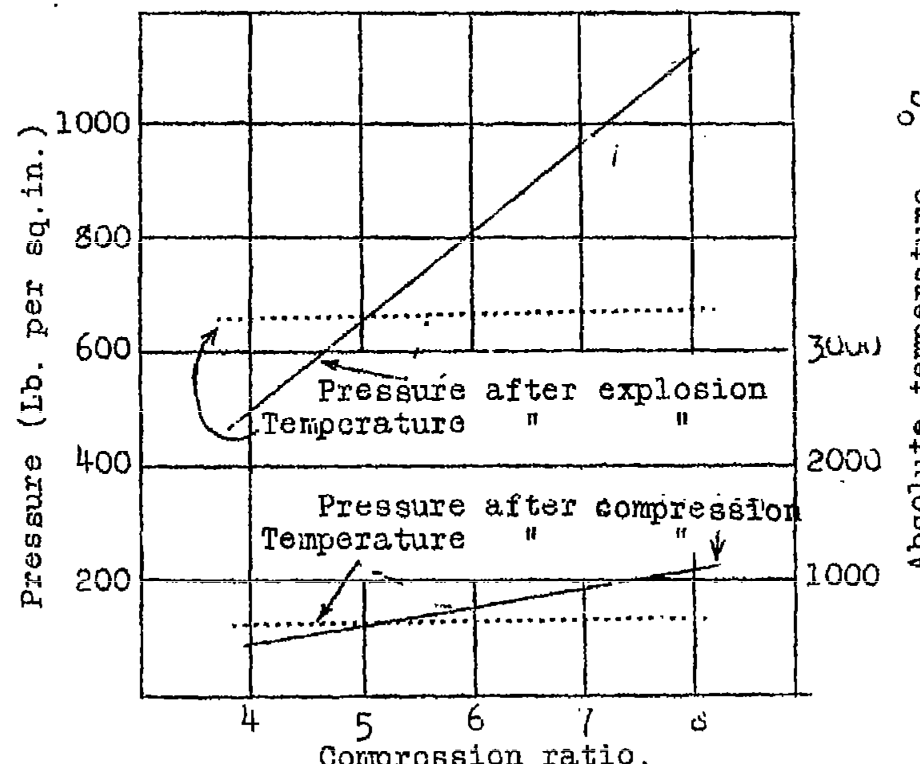
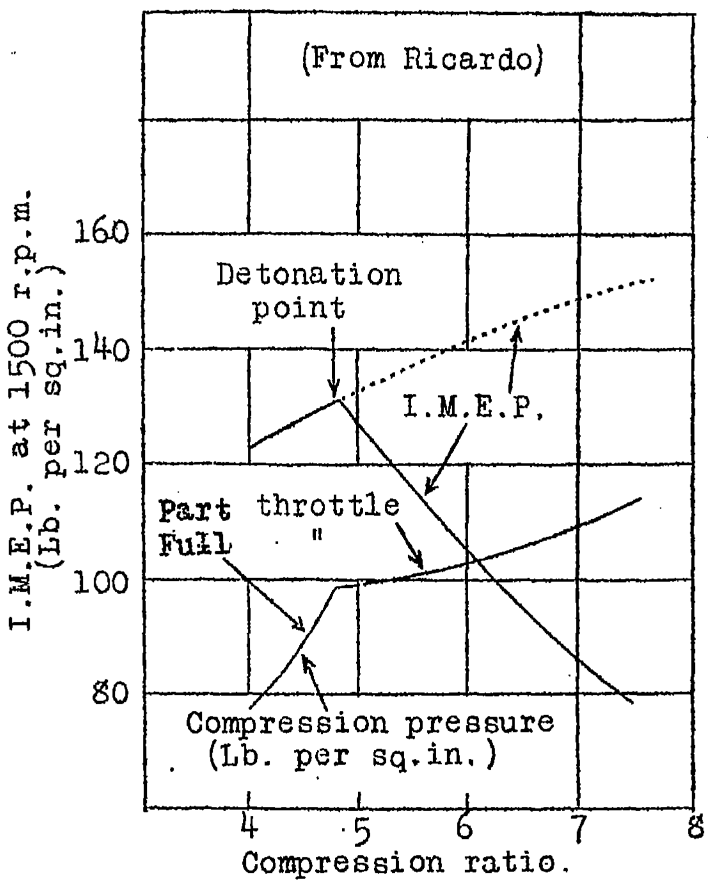
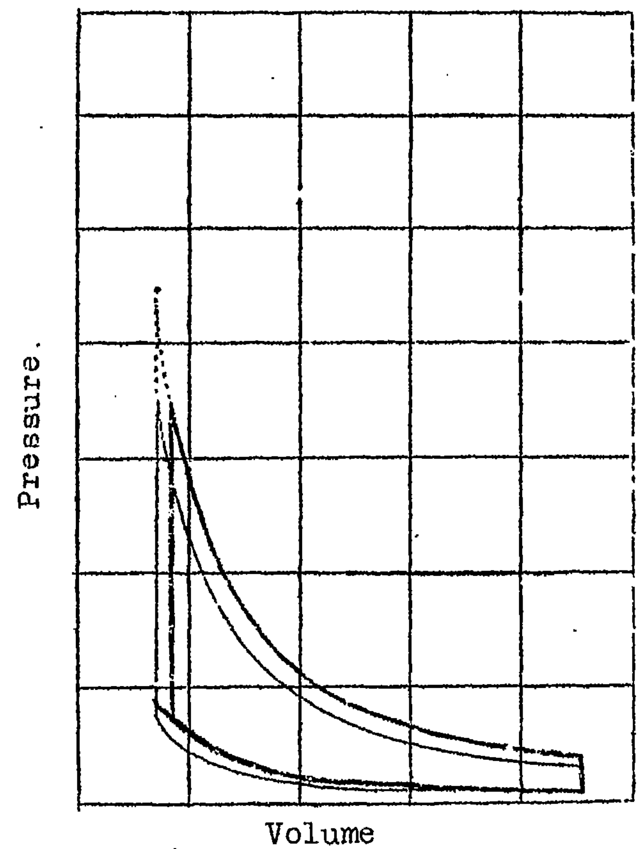

Pressure (Lb. per sq.in.)
1000
800
600
400
200
Absolute temperature - °C.
3000
2000
1000
Pressure after explosion
Temperature " "
Pressure after compression
Temperature " "
4
5
6
7
8
Compression ratio.

Fig. 2.



(From Ricardo)
I.M.E.P. at 1500 r.p.m. (Lb. per sq.in.)
160
140
120
100
80
Detonation point
I.M.E.P.
Part throttle
Full "
Compression pressure (Lb. per sq.in.)
4
5
6
7
8
Compression ratio.

Fig. 3.



Pressure.
Volume

Fig. 4.

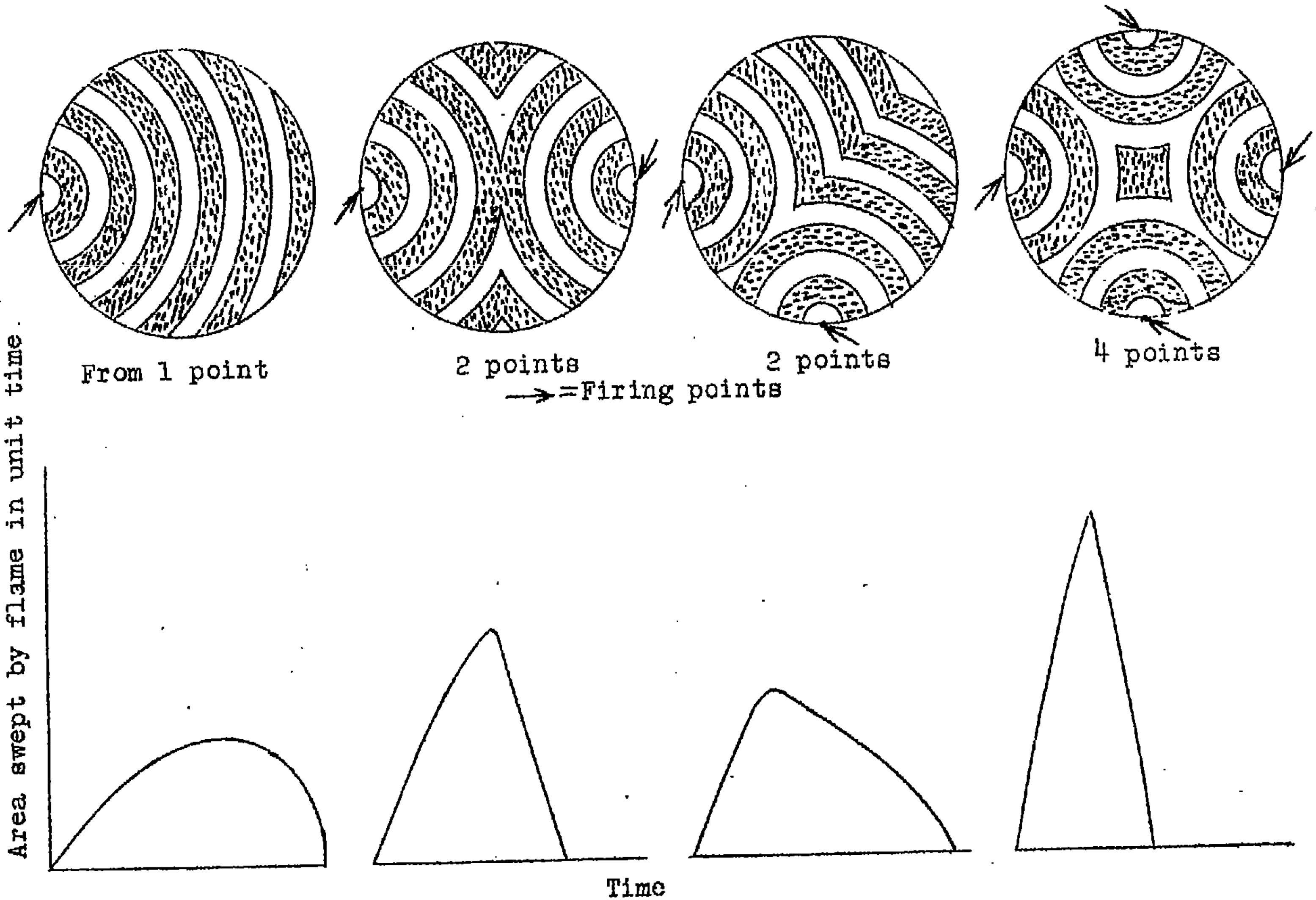

From 1 point
2 points
2 points
4 points
=Firing points
Area swept by flame in unit time
Time

Fig. 5.